FINAL TECHNICAL REPORT

Paleoseismic investigation of the Miller Creek fault, eastern San Francisco Bay area, California

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PALEOSEISMIC INVESTIGATION OF THE MILLER CREEK FAULT, EASTERN SAN FRANCISCO BAY AREA, CALIFORNIA

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TECHNICAL ABSTRACT

The region between the Hayward and Calaveras faults includes folded late Cenozoic strata and has been viewed as a domain dominated by contractional deformation. The Miller Creek fault is subparallel to the Hayward fault and has been interpreted as having accommodated the largest amount of late Cenozoic shortening of faults within the domain. However, evidence from our trenching investigation of the Miller Creek fault in the Upper San Leandro Reservoir area, adjacent to Big Burn Road, indicate a significant component of late Quaternary lateral movement on the fault. Evidence includes tectonic inversion of colluvial graben-fill, low-angle slickensides, and flower structures on high-angle faults. Consistent with lateral movement, the N25°W-striking fault appears to have a steep dip, about 80°SW, estimated from the geometry of the fault trace over 150 m of topographic relief in the vicinity of the trench.

The Big Burn Road trench exposed a ≥30-m-wide zone of numerous faults and minor shears that offset and deformed several colluvial units. The steeper faults, including the interpreted main fault, exhibit low-angle slickensides, whereas moderately-dipping faults display down-dip slickensides and reverse fault sense-of-shear indicators. A moderately NE-dipping fault marked by an up to ≤20-cm-wide gouge zone, drag folds one of the upper colluvial units and displaces it about 0.2 to 0.5 m in a reverse sense. This colluvial deposit is probably Holocene to latest Pleistocene in age, based on a lack of distinct soil horizonation. Directly above the steeply southwest-dipping main fault, a stoneline at the base of the most recent colluvial deposit (mean residence time ^{14}C dates of 700 to 1000 years) is arched (amplitude of arch ≤20 cm), but apparently not faulted. This possible fold may be due to swelling of expansive clays that makeup much of the colluvial unit, or it may be due to movement on the underlying main fault. If this is a tectonic fold, then it represents at least minor surface-faulting during late Holocene on the Miller Creek fault at this site; although the amount of associated net slip cannot be accurately estimated because of an unknown but apparently dominant lateral-slip component.

Another trench was excavated across an alluvial fan concealing the Miller Creek fault at King Canyon about 3 km northwest of the Big Burn Road trench. This trench exposed a thick sequence of alluvial deposits and buried soils that overlie the fault's bedrock trace, including a continuous and unbroken deposit with an age of ≥16,000 ^{14}C yr BP. Thus, in contrast to the Big Burn Road site, there is no evidence for Holocene or latest Pleistocene movement on the Miller Creek fault at this site. Different fault behavior along this reach also coincides with the fault having a more northwesterly strike, N40°W, and a shallower dip, 60°SW, estimated on the basis of the geometry of the fault trace over about 200 m of topographic relief. Activity along the central Miller Creek fault may step eastward from the vicinity of Big Burn Road to the subparallel Cull Creek fault, which continues northward as the Moraga fault, although no cross-over structures have been identified.

NON TECHNICAL ABSTRACT

In the region between the Hayward and Calaveras faults, in the eastern San Francisco Bay region, the Miller Creek fault has the largest amount of accumulated movement within the last 10 million years. Our trenching investigation indicates that the level of activity on the Miller Creek fault within the last tens of thousands of years is much lower than the long-term displacement rate averaged over the last 10 million years. Our trenches exposed evidence of possible fault movement in the last 2,000 years and probable fault movement within the last 10,000 years. The recurrence of earthquakes on this fault within the past tens of thousands of years is on the order of several thousand years. Faults in this region have previously been assumed to have been thrust or reverse faults (rocks on one side of the fault move up and over rocks on the other side of the fault). Data from our investigation indicate that the Miller Creek fault is predominantly a strike-slip fault (one side of the fault moves horizontally past the other side). The strike-slip style of faulting on the Miller Creek fault indicates that the region between the Hayward and Calaveras faults behaves differently than previously thought, and that future fault investigations in this region need to plan for investigation of strike-slip faulting.

BIBLIOGRAPHY OF PUBLICATIONS RESULTING FROM THIS PROJECT:

Wakabayashi, J., and Sawyer, T.L., 1998, Holocene (?) oblique slip along the Miller Creek fault, eastern San Francisco Bay Area, California (extended abstract): EOS, v. 79, no. 45, p. F613

INTRODUCTION: REGIONAL TECTONIC SETTING

Faulting and Deformation in the Eastern San Francisco Bay Region

In the San Francisco Bay region the San Andreas fault system accommodates approximately 40 mm/yr of dextral slip rate (e.g., Argus and Gordon, 1991). All, or nearly all of this slip rate is distributed on the major strike slip faults of the system, from west to east, the San Gregorio, San Andreas, Hayward, Calaveras and Greenville faults. Although fold and thrust belts in late Cenozoic rocks are well developed in the regions adjacent to or between the major strike-slip faults, the total regional shortening rate across the California Coast Ranges is less than or equal to about 3 mm/yr (Argus and Gordon, 1991). There are local areas of significant shortening, such as the Mt. Diablo region (Unruh and Sawyer, 1995; 1997), that are driven by local contractional step overs or bends within the transform fault system. In addition to the local effects, the relatively broad limits of geodetically-based regional shortening rate (e.g., Argus and Gordon, 1991) hypothetically permit slip rates as high as 1 to 2 mm/yr on individual thrust systems. Slip rates in the 1 to 2 mm/yr range potentially constitute significant seismic sources, depending on their locations relative to the more active major strike-slip faults.

In the eastern part of the San Francisco Bay area (East Bay) (Fig. 1), the Hayward, Calaveras and Greenville faults are the major strike-slip faults and their estimated dextral slip rates are 8 to 10 mm/yr, 4 to 6 mm/yr and 1 to 3 mm/yr, respectively (Lienkaemper et al., 1991; Kelson et al., 1994; Unruh and Sawyer, 1997; Unruh and Lettis, 1998). Shortening rates in the intervening regions have been estimated in only a few areas, and these estimates have been long-term late Cenozoic rates, not latest Quaternary rates that can be directly applied to seismic hazard evaluation.

The region between the Hayward and Calaveras, herein referred to as the East Bay Hills, is underlain by mostly Cretaceous Great Valley Group sandstones and shales and Tertiary (mostly Miocene) sedimentary and volcanic rocks that are involved in km-scale folds. In addition to the folds, several faults that extend for several km or more displace the Miocene strata in this area. Most of the fold axes and faults in this region are parallel to subparallel to the strike of the Hayward fault (e.g., Graymer et al., 1994). These relationships have been interpreted as evidence for significant late Cenozoic shortening perpendicular to the Hayward fault (i.e., perpendicular to average strike of the San Andreas fault system) (e.g., Wakabayashi et al., 1992). Although post-Miocene average shortening rates are as high as 1 mm/yr in the East Bay Hills (Wakabayashi et al., 1992), the connection between the averaged late Cenozoic shortening rate and latest Quaternary fault activity has not been well documented.

One of the objectives of this study is to better understand the nature of latest Quaternary faulting in this region by investigating one of the major faults in this region, the Miller Creek fault.

Miller Creek and Related Faults

Regional Extent of Faults

Of faults in the East Bay Hills, the Miller Creek may have the largest late Cenozoic separation. Although interpreted as a purely reverse or thrust fault with several km of reverse displacement by some previous studies (e.g., Wakabayashi et al., 1992), new correlations of late Cenozoic volcanic rocks in the East Bay and consideration of regional geologic constraints, indicates that cumulative dextral slip may greatly exceed reverse slip. Part of the Miller Creek fault may accommodate a substantial portion of an estimated 35 km of post-10 Ma dextral slip that occurs between the Hayward and Calaveras faults (Wakabayashi, 1997; Wakabayashi, in review), and has been interpreted to separate regions of contrasting late Cenozoic stratigraphy (Jones et al., 1994; Graymer et al.,1994).

South of our study area in the Upper San Leandro reservoir region, the Miller Creek fault may connect to the Palomares fault (Crane, 1988; Jones et al., 1994; Graymer et al., 1994). North of Upper San Leandro Reservoir, the Miller Creek fault has been interpreted to connect with the Moraga fault (e.g., Graymer et al., 1994; Wagner, 1978). However, detailed mapping in the Upper San Leandro Reservoir area indicates that the Miller Creek fault cannot directly connect with the Moraga fault and instead continues along the faulted contact between the Miocene strata of the Monterey and Contra Costa Group (Wakabayashi et al., 1992; Buising and Wakabayashi, 1996; A. V. Buising unpub. mapping). Northward, the Miller Creek fault as defined by Wakabayashi et al. (1992), a definition adopted in this report, may merge with the Wildcat fault.

The other faults that may accommodate significant amounts of late Cenozoic dextral slip include the Cull Canyon fault that, according to detailed mapping connects to northward to the Moraga fault, the Bolinger and Las Trampas faults (Wakabayashi et al., 1992; Buising and Wakabayashi, 1996). These faults have also been interpreted in the past as purely reverse or thrust faults (Ham, 1952; Wakabayashi et al., 1992).

Although the Miller Creek and parallel faults such as the Cull Creek fault are significant late Cenozoic faults, latest Quaternary activity on these faults is not well constrained. The Miller Creek and related structures do not appear to be associated with any significant seismicity (Oppenheimer and Lindh, 1992; Oppenheimer et al., 1992). The Miller Creek fault appears to have or have had a dip-slip component of movement, and alluvium may be ponded on the downthrown (upstream) side of the fault (Wakabayashi et al., 1992) (Fig. 2). Reconnaissance trenching associated with earlier investigations revealed bedrock faults, and possible faulted colluvium, but did not find evidence to constrain late Quaternary activity on the fault (Wakabayashi et al., 1992). Based on a model of pure thrusting faulting on the Miller Creek and related faults Wakabayashi et al., (1992) estimated shortening rates (averaged over the last 3.5 to 6 million years) of approximately 1 mm/yr associated with the Miller Creek fault. This estimated shortening rate may be of little relevance to late Quaternary activity on the Miller Creek fault for several reasons including: (1) The San Andreas fault system, including the eastern part of the system, has experienced numerous shifts in slip rate partitioning over the last 6 million years, including a major shift within the last million years (Wakabayashi and Hengesh, 1995; Wakabayashi, 1997; Wakabayashi, in review). (2) Deformation between the major strike-slip faults of the San Andreas system (in this case the Calaveras and Hayward faults) commonly migrates through a region, resulting in changes in rates and styles of deformation on time scales of hundreds of thousands of years or less (Hengesh and Wakabayashi, 1995; Wakabayashi and Hengesh, 1998); (3) The assumption of no strike-slip faulting through the area, that is critical to the estimation of shortening rate, is probably invalid based on evidence for major late Cenozoic dextral slip through this area, much of which may have occurred since 6 Ma.

Kelson and Simpson (1994) estimated late Quaternary uplift rates in the 1 mm/yr range in Niles Canyon (Fig. 1). If such uplift rates extended further northwest to the region of the Miller Creek fault, high late Quaternary shortening rates may be indicated for the Miller Creek and related faults. In addition to uncertainty in the significance of the long-term estimate of shortening rate on the fault, ~ 2 mm/yr uncertainties in the dextral slip rates on the Hayward and Calaveras faults (Lienkaemper et al, 1991; Kelson et al., 1992; 1994) and the overall slip rate budget in the eastern part of the San Andreas fault system are permissive of dextral slip rates of 1 to 2 mm/yr being accommodated on the Miller Creek and related faults. Such possible deformation rates would make the Miller Creek a significant local source of seismic hazard to communities such as Moraga and developments in Palomares Canyon, areas of rapid population growth.

We conducted detailed paleoseismic trenching of the Miller Creek fault to better constrain latest Quaternary activity on this structure. The results of this investigation are detailed below.

The Miller Creek Fault in the Upper San Leandro Reservoir Area

In the Upper San Leandro Reservoir area, the Miller Creek fault separates the well-sorted arkosic sandstones, cherts and siliceous shales of the Miocene Monterey Group on the west, from the mudstones, siltstones, poorly sorted sandstones and conglomerates of the late Miocene Contra Costa Group on the east (Wakabayashi et al., 1992) (Fig. 2). Several small slivers of Miocene San Pablo Group sandstones are also present along the fault (Fig. 2).

Based on the trace of the fault and topography (~100 m of vertical relief), the fault appears to strike about N35°W and dip 60° southwest in the vicinity of King Canyon (Trench 1) and strike N23°W and dip 82° southwest crossing the ridge on which the Big Burn Road trench site (Trench 2 in Fig. 2) is situated. The steeper dip appears to be maintained south of the Big Burn Road site. The stratigraphic contrast across the fault and the southwesterly dip indicates reverse separation, but much of this separation may be an artifact of large-scale dextral slip as noted earlier.

In the Upper San Leandro reservoir area, the Miller Creek fault appears to have two branches: one, with the greatest stratigraphic separation, separates Contra Costa from Monterey Group, the other separates the Claremont Chert member of the Monterey Group from siliceous shales and sandstones of the Monterey Group (Wakabayashi et al., 1992) (Fig. 2).

EXPLORATORY TRENCHING

Trench Site Selection

The detail and resolution of the paleoseismic record in an exploratory trench depends chiefly on the nature, character, and continuity of the exposed deposits. Depositional hiatuses represented by unconformable stratigraphic relations may signify "gaps" in the paleoseismic record. The record can be greatly complicated by mass wasting processes, to the point of being indecipherable. In the absence of peats, alluvial deposits are desirable because they are often relatively extensive and occur in distinctly layered sequences. Although generally not providing as complete a stratigraphic record as alluvial sites, colluvial sites also may provide useful paleoseismic information.

In this investigation, priority was given to sites in alluvial depositional settings of low relief that received frequent and recent deposition. However because the Miller Creek fault is in a hilly region of locally significant relief and juxtaposes competent rock of the Monterey Group against poorly consolidated sediments of the Contra Costa Group, such sites are rare along its length.

Three alluvial sites and one colluvial site were identified based on photogeologic analysis of historical aerial photographs and considered for a paleoseismic trench investigation of the Miller Creek fault. One of these sites, where the fault crosses Miller Creek, was rejected because of recent and extensive ground disturbance associated with construction of the new Upper San Leandro Reservoir dam.

A second site in the Kaiser Creek arm of the reservoir was rejected during field reconnaissance because the site had received several feet of alluvial deposits in the recent historical period; alluvial-fan deposits have buried much of a barbwire fence. Therefore, it is unlikely that a backhoe trench would be sufficiently deep to expose deposits old enough to record the movement history of the fault.

Thus, we excavated an exploratory trench at the third alluvial site, "King Canyon site", which is in the King Canyon arm of the reservoir. Subsequently we excavated a second trench at the colluvial site, "Big Burn Road site", on the drainage divide between Kaiser Creek and Riley Canyon (Fig. 3).

King Canyon Site

The King Canyon site is on the south side of the King Canyon arm several meters above the maximum reservoir level and near the border between Contra Costa and Alameda counties (Figure 3). An unnamed tributary to King Canyon has deposited an alluvial fan that covers the Miller Creek fault at the site and extends onto the floor of the canyon. Colluvial deposits bury the west edge of the alluvial fan along the base of a steep slope underlain by the resistant rocks of the Monterey Group. Poorly consolidated rocks of the Contra Costa Group are exposed on the hillslope east of the alluvial fan (Fig. 3).

A 45-m-long angled trench was excavated at the King Canyon site to a maximum depth of 4.35 m (Plate 1). The west end of the trench was at the base of the steep east-facing bedrock slope. The trench extended across the flanking colluvial slope and part way across the alluvial fan (Fig. 4). Monterey Group bedrock overlain by a westward (upslope)-thinning sequence of colluvium was exposed near the west end of the trench. In the west-central part of the trench, these colluvial deposits grade into, interfinger with, and overly alluvial deposits. The thick sequence of alluvium rests on bedrock and was exposed to the east end of the trench. Two large test pits were excavated on the colluvial slope prior to siting the trench. The pits exposed bedrock overlain by colluvium.

A hand-auger hole was excavated in the floor of the trench near the east end (Plate 1). This borehole extended to a total depth of 9.5 m below the ground surface and approximately 1 m into pebbly sandstone or conglomerate of the Contra Costa Group (Plate 1). The boring indicates that the alluvial sequence is at least 8.65 m thick at the site. Most critically, the boring demonstrates that the trench crossed the contact between the Contra Costa Group and the Monterey Group and, therefore, straddled the Miller Creek fault. This is critical because no faults or fault-related deformation was found within the surficial deposits in the trench.

Bedrock Stratigraphy

The King Canyon trench exposed bedrock of the Miocene Monterey Group. In addition, the hand-auger hole in the floor of the northeastern part of the trench cored late Miocene Contra Costa Group.

Well sorted, arkosic, low lithic sandstone of the Monterey Group (Tmss) is exposed in the southwestern part of the trench (Plate 1). This sandstone is grayish orange on fresh surfaces and is moderately well sorted, moderately well cemented and moderately weathered (milky feldspars). This rock has zones of pervasive iron oxide staining. Fracture spacing is ≥10 cm and no internal lamination is discernible. The Monterey Group rocks fine to southwest in the trench.

This sandstone grades from a medium grained sandstone to light brown siltstone (Tmsi). Locally the finer grained rocks contain some organic material (wood, vegetative fragments) and small bivalves about 1 cm in size. The finer grained rocks are generally moderately well cemented but locally hard. Fracture spacing ranges from <1 cm to 10 cm. Internal lamination difficult to identify, but orientation of fossils indicates steep bedding. Color below upper limit of groundwater-altered zone is grayish green when wet, and dusky green, grayish green, or dusky blue green, when dry.

Poorly consolidated grayish green pebbly sandstone or conglomerate of the Contra Costa Group (Tmcc) was sampled with the hand auger boring. The sandstone/conglomerate is poorly sorted and contains well rounded cobbles of Franciscan Complex basaltic volcanics, sandstone and red chert. Subrounded or subangular cobbles are lacking, as are cobbles of Monterey Group rocks, that are common in the overlying colluvial and alluvial deposits.

Surficial Deposits

The King Canyon trench exposed four alluvial deposits and three colluvial deposits (Plate 1). A modern and two buried soils were identified, which represent significant depositional hiatuses within the sequence of surficial deposits Table 1. Both buried soils have been truncated showing that these hiatuses were coincident with periods of erosion.

The two uppermost alluvial deposits, units A1 and A2, are similar. They extend from the east end of the trench to about station 20S (i.e., 20 meters from east end of trench on the south wall), where they grade gradually into the two uppermost colluvial units (units C1 and C2 in Plate 1). These deposits are well sorted, fine grained, and very dark grayish brown to black (respectively). Clasts are infrequent, subrounded sandstone and subangular to angular chert derived from the Monterey Group. However, clasts are common within a discontinuous locally well-developed stoneline at the base of unit A1. The matrix of both units is a plastic, silty clay loam. The compound structure of the lower part of alluvium A1 and throughout alluvium A2 is strong, medium to coarse subangular blocky and strong, coarse to very coarse prismatic. East of station 3S, unit A2 contains a coarse, gravelly channel-fill deposit. The modern surficial soil has developed within unit A1 and the uppermost buried soil occurs within unit A2 (Table 1). Randomly oriented, pedogenic slickensides on some prismatic ped faces within these vertisolic to mollisolic soils indicate the presence of expansive clay minerals.

Unit A3 is the next oldest alluvial deposit exposed in the trench and occurs east of stations 25S (Plate 1). This generally finning-upward unit contains layers of moderately sorted pebble to gravel and sandy gravel with abundant subangular sandstone clasts. The alluvium contains several small channel-fill deposits east of about station 8S and a relatively large channel sequence between stations 17S and 21S. The dark brown clayey matrix is sticky to very sticky and very plastic. The gravelly layers are clast supported. Clay films in the upper part of alluvium A3 are common and moderately thick where they coat pores and are infrequent and thin on ped faces. The structure of this unit is medium to coarse subangular blocky and is moderately to strongly expressed near the top of the unit, but is less distinct with depth. Between station 11S and 25S, unit A3 is a relatively large channel-fill deposit inset in the older A4 alluvial channel.

The oldest alluvial unit in the King Canyon trench, unit A4, occurs east of station 25S (Plate 1). The matrix is a dark grayish brown clay loam that has been reduced below the water table, which is evident by its bluish gray color. Clay films are absent within this massive alluvium. Between stations 10S and 12S krotovina and apparently associated small fragments of charcoal are present. The lowermost buried soil has developed with in this and overlying unit A3.

The two uppermost colluvial units, C1 and C2, grade laterally into alluvial units A1 and A2 (respectively) near the middle of the trench. Colluvium C1 is continuous and gradually tapers towards the west end of the trench. Colluvium C2 has been eroded out near station 28S and is preserved in isolated bedrock pockets west to about station 32S (Plate 1). Erosion of unit C2 was associated with deposition of overlying colluvium (C1) as evidenced by the stoneline at the base of that unit. These moderately to poorly sorted units contain angular to subangular sandstone clasts supported in clayey silt matrix. They have weak to moderate subangular block structure. Fine-grained materials from these units have translocated 30 cm or more along fractures into the underlying bedrock.

The oldest deposit in the Kings Canyon trench, colluvium C3, extends between station 21S and 26S (Plate 1). This unit is a massive gravel to cobble conglomerate containing strongly weathered subrounded sandstone clasts in a slightly sticky and slightly plastic clay loam matrix. Generally the matrix is dark yellowish brown, but below the water table is a grayish blue. Many thick to moderately thick clay films line pores within this unit, which lies directly on bedrock. Part of the unit may be *in situ* disintegration and (or) bioturbation of the rock mass.

Age of Surficial Deposits

Datable materials were only found in the oldest exposed alluvial deposit, unit A4, at about station 11S-3.5 (Plate 1). This material was collected in three samples that were submitted for accelerator mass spectroscopy (AMS) radiocarbon dating. Sample RC1 was a small charcoal fragment (1.5 cm x 1 cm x 1 cm) that yielded an AMS date of 6,190±50 ^{14}C yr (Table 2). Sample RC2 was collected at approximately the same stratigraphic level as RC1 and consisted of several small charcoal fragments. The date on this sample is 16,330±60 ^{14}C yr. The third sample, RC3, consisted of two small carbonized wood fragments (2 cm x 1.5 cm x 0.5 cm and 1 cm x 1 cm x =0.5 cm) that yielded a AMS date of 6,320±50 ^{14}C yr.

These organic materials were collected from stratigraphically below the modern surficial soil and a buried soil, and from within an underlying second buried soil. The diagnostic property of the overlying buried soil is the presence of moderately thick clay films on ped faces indicating that translocated clays have accumulated within this soil. Therefore, the upper buried soil has a Bt horizon (Table 1). Thin clay films also occur within the lowermost buried soil.

The two younger dates appear to be spurious based on the rates of soil development in the region. The clay content in B horizons increases with increasing soil age (e.g., USDA, 1975). Helley and others (1979, p. 62) reported that 4,000 to 6,000 year old loamy soils in the San Francisco Bay area typically lack clayey B horizons. Shlemon (1981) described soils with thin clay films in Livermore Valley that he estimated to be no older than about 15,000 years old.

These relationships suggest that each of the buried soils represent a period of soil formation on the order of 4,000 to 15,000 year, implying that unit A4 is late Pleistocene in age. A late Pleistocene age is consistent with the is 16,330±60 ^{14}C yr date on sample RC2 (Table 2).

The apparently erroneous dates on samples RC1 and RC3 may indicate that the dated charcoal material was secondary in nature. This claim is bolstered by the presence of an obvious krotovina filled with gravelly materials in close proximity to the sample locations (Plate 1). The possibility that these were secondary materials was noted when the samples were collected. It is possibly that all three dates were on secondary materials and, thus, provide minimum limiting ages for the alluvial sequence and the associated colluvial deposits.

<u>Exposed Faults</u>

Faults exposed in the King Canyon trench are confined to rocks of the Miocene Monterey Group, and do not extend into the overlying surficial deposits (Plate 1). There are two general sets of faults. One set consists of moderate- to high-angle faults that occur between stations 32S and 40S. These are generally planar to anastomosing, northeast-striking faults that dip from about 40°E to near vertical. The faults tend to widen upwards and are commonly infilled with tongues of soil material that have been disrupted by bioturbation. The faults are also associated with pockets or depressions in the top of the bedrock, apparently resulting from differential erosion of the more highly fractured rock within the fault zone prior to deposition of the colluvial sequence. There is no discernible offset of the bedrock surface across these faults and no evidence of fractures or shear fabric was found during careful examination of the overlying colluvium.

The second set of faults dip gently to the east and south and occur in the western part of the trench. The most conspicuous of these faults, extends from near stations 38S to about station 44S.

The upper end of this fault terminates at one of the higher-angle faults. This irregular fault strikes N36°E to N56°E and dips 21°S. Slickensides on the fault plane trend S33°E and plunge 11°SW. The same fault is exposed in the north trench wall where it is oriented N7°E43°E and exhibits dip-slip slickensides. On both walls the fault truncates bedding contacts within the Monterey Group.

Evaluation of the King Canyon Site

The King Canyon trench bottomed in sandstone of the Monterey Group at the west end and in a thick sequence of alluvial-fan deposits at the east end. A hand-auger borehole near the east end encountered sediment of the Contra Costa Group. Therefore the trench straddled the contact between these formations, which is known from detailed bedrock mapping in the immediate area to be controlled by the Miller Creek fault (Wakabayashi et al., 1992) (Fig. 2).

Alluvium A4 is a late Pleistocene (16 ka or more) deposit that is continuous and unbroken from where it rests on Monterey Group sandstones and siltstones to where it overlies conglomerate of the Contra Costa Group. Therefore, this deposit provides positive evidence for an absence of Holocene fault activity on the northern Miller Creek fault at the King Canyon site.

Big Burn Road Site

The second trench was excavated at the colluvial Big Burn Road site, which is immediately south of Big Burn Road where the fault crosses the drainage divide between Kaiser Creek and Riley Canyon (Figure 3). The fault is expressed at this site by a steep east-facing escarpment underlain by rocks of the Monterey Group and a prominent vegetation contrast from thick brush to the west and annual grasses to the east (Figure 5).

ESA (1991) excavated a trench at this site as part of their seismic hazards investigation for the Upper San Leandro Reservoir dam. Although the Miller Creek fault was exposed its activity was considered to be indeterminate.

We excavated a 35-m-long trench at the Big Burn Road site (Figure 5) that was adjacent the ESA (1991) trench alignment on the south. The trench, which was up to 4.25 m deep, extended part way up a steep east-facing slope and to the approximate axis of a asymmetric topographic saddle on the rounded ridge crest. Bedrock of the Miocene Monterey Group was exposed in the western half of the trench and late Miocene Contra Costa Group were exposed near the east end. A sequence of colluvial deposits were exposed throughout the trench.

Bedrock Stratigraphy

Contra Costa Group rocks exposed in the eastern part of the trench site (stations 24S to 31.5S) include mudstones, sandstones and conglomerates (Plate 1). Block-in-matrix, melange structures are developed in the siltstone and mudstone with these lithologies forming sheared matrix and the same lithologies or coarser ones (sandstones and conglomerates) forming blocks. Bedding can be recognized because of relatively closely spaced interbedding and changes in lithology.

Dark yellowish orange medium-grained sandstone (Tcss) was encountered between stations 29.5S and 31.5S and 25S to 26S. This sandstone is poorly sorted (in sand fraction many pebble size grains) but is relatively low in clay or silt fraction. Lithic clast content is relatively high. Abundant oxidized siltstone clasts (probable Monterey Group clasts) are present. This rock is moderately hard and strong and moderately weathered.

Pale olive to light olive gray muddy siltstone to mudstone (Tcsi) was encountered between stations 24S and 29.5S. This rock contains containing cm-scale pockets of sand. This rock is of low hardness and moderately strong and is moderately to lightly weathered. Locally this rock is grayish red mudstone and is soft and weak with 1-3 cm pockets of powdery carbonate or zeolites. Locally this unit is finer grained (siltstone to mudstone) and is moderate olive brown with siltstone pockets. From stations 24S to 27S this rock exhibits shear foliation and forms block in matrix structure with phacoids/boudins of conglomerate and hard fine grained sandstone. This rock is of low hardness and moderately weathered. This fine grained sandstone is light olive gray . The sandstone has high mud and silt content. Conglomerate boudins and horizons (Tcc) are yellowish gray to dusky yellow. The conglomerate is matrix supported with a large amount of relatively clean sand. Rounded to subrounded clasts range up to 3 cm in size. Franciscan lithologies such as red chert, greenstone, and greywacke are common as are quartz clasts (clasts derived from veins). Laminated Claremont chert clasts are also present.

Rocks of the Monterey Group exposed in the western part of the Big Burn Road trench (stations 0S to 18S) consist of sandstones, siltstones and mudstones with some interbedded chert. There is some gradation between the various lithologies. Bedding could be easily recognized in most of the rocks of this unit because of interbedding of different lithologies. Block-in-matrix, melange structures were observed in this unit.

Light yellowish gray (Tmss) fine grained, well sorted sandstone is present between stations 9S and 13S. This sandstone is quartz rich, lithic poor, and well cemented; hard and strong when fresh or little weathered much softer when weathered. The only fresh exposures are as blocks in a sheared matrix of siltstone or mudstone, continuous exposures are moderately to deeply weathered.

Pale yellowish brown siltstone to mudstone (Tmsl) are exposed between stations 0S and 10S. This rock exhibits yellowish and orange iron oxide coatings and is soft, weak and deeply weathered. Local interbeds of deeply weathered, dark yellowish orange 10YR6/6 siltstone to fine sandstone. These also occur as lenses or phacoids. These oxidized, deeply-colored rocks are easily identified as clasts in surficial deposits. Shear foliation is common, particularly in the mudstone. Similar siltstone that grades to fine sandstone is present between 8S and 18S.

Interbedded chert with mudstone (Tmcs) was observed between stations 1S and 6S. Chert is black to dusky brown; and mudstone is as described above. Chert beds range up to 2 cm in thickness, very rare laminated beds occur, chert content of package varies from about 70% to <20%. Of particular note is the *absence* of light-colored, laminated chert and porcellanite, that is common in the Claremont Chert member of the Monterey Group that crops out about 100 m to the west of the trench site on the ridge (Fig. 5). Chert beds are commonly boudinaged and the unit as a whole is moderately weathered.

Surficial Deposits

The Big Burn Road trench exposed fill from the ESA (1991) trench, seven colluvial units, and one alluvial subunit (Plate 1). All but the oldest colluvial deposit appear to have been derived from the hillslope immediately adjacent to the west end of the trench (Fig. 5). The relative age of the colluvial deposits is based on stratigraphic position and the degree of soil development. However, one colluvial deposit in the western part of the trench is separated by a fault from the other colluvial units and has no relative age assignment. The uppermost colluvial deposit contains the modern soil and the subjacent deposits contain two relict buried soils (Table 3).

The youngest colluvial deposit, unit C1, extends the entire length of the trench and is up to 90 cm thick. This bioturbated unit contains mostly subangular to subrounded Monterey sandstone clasts up to 10 cm in diameter and some angular laminated chert clasts. The clasts are supported in a silty fine-sand matrix. A well-developed stoneline locally occurs at the base of this unit and between stations 5S and 10S is delineated as a subunit up to 20 cm thick. Thus the contact between this colluvium and the subjacent unit, C3, is an erosional unconformity.

Unit C2 is an interlayered package of colluvium consisting of five subunits. In general this deposit is a dark grayish brown, sandy clay with less than 5% gravel. Clasts lithologies are primarily siltstone and sandstone with minor amounts of laminated chert. This unit is unique because it contains the largest krotovina exposed in the trench and the internal contacts separating the subunits are subhorizontal rather than parallel to ground surface. In addition, the only alluvial deposit exposed in the trench is associated with this unit. This alluvial deposit is a channel infilling and associated lag deposits inset into the third lowest subunit and covered by the uppermost subunit.

Colluvium C3 in nearly continuous from station 6S east to the end of the trench. This deposit consists of very plastic clay with scattered gravel (5 to 8 %) and some gravel layers. The clasts are primarily sandstone, but the upper part of this unit has been logged as a separate subunit based on the presence of predominantly laminated chert clasts between stations 11S and 16S (Plate 1). East of station 25.5S, the colluvium is derived from siltstone and sandstone of the Contra Costa Group. Here the matrix is olive gray clayey silt. The most distinctive feature of this entire unit is strong coarse prismatic structure compounded with angular blocky structure which is associated with the well-developed upper buried soil. Locally this colluvium is inset into unit C5.

Unit C4 occurs between stations 1S and 9S, and contains a few discontinuous and irregular contact between the subunits (Plate 1). The upper subunit is a sandy gravel with 50 to 60 percent gravel consisting of angular clasts as much as 20 cm in diameter. The intermediate subunit contains 10 to 15 percent angular clasts up to 5 cm in a pale brown silty sand matrix. The lowest subunit is siltstone-rich and contains some dark chert and some laminated chert clasts up to 3 cm in diameter. The original size of the siltstone clasts is difficult to estimate because of the advanced degree of weathering. This unit is in fault contact with underlying unit CX and it rests unconformably on the wavy to irregular top of the Monterey Group.

The next stratigraphically lower unit, C5, is clast supported and extends from station 11S to about station 21S (Plate 1). The upper subunit is composed almost entirely of sandstone and siltstone gravel of the Monterey Group in a plastic clayey matrix with one block of siltstone that is over a meter long. The underlying subunit rests on Monterey bedrock and consists of sandstone and siltstone gravel with almost no matrix. Locally a stoneline is present at the base of this subunit. The lowest subunit consists of about 40 percent laminated chert and sandstone clasts in a sandy matrix. One isolated pocket of colluvium C5, between stations 25S and 26.5S, overlies and is derived from a conglomerate bed within the Contra Costa Group. Here the unit is a gravelly sand. Colluvium C5 is inset into colluvium C6 and, between stations 24S and 25S, these deposits are separated by an high-angle angular unconformity.

A silty clay colluvium with 60 to 80 percent rock fragments, unit C6, occurs between stations 17.5S and 25S (Plate 1). Angular fragments of laminated chert are 5 to 10 times more abundant than other lithologies, which included black silicified shale and sandstone of the Monterey Group and siltstone and sandstone of the Contra Costa Group. Most lithic fragments are 5 cm and less, however, the deposit contains isolated blocks of siltstone and sandstone that are up to 185 cm long. These blocks and the internal contacts are oriented subparallel to the ground surface in the western half of this unit, but are oriented near vertical in the eastern part where the unit is internally sheared. In general the weak imbrication of clasts also mimics this pattern. This fault-bounded unit appears to be an infilling within a large-scale fissure or graben. The base of the unit is not exposed, but its apparent thickness is at least 3 m.

Pale brown sandy silt, colluvium CX, occurs between stations 0.4S and 5S in the footwall of the westernmost fault exposed in the Big Burn Road trench (Plate 1). Angular fragments of laminated chert and subangular blocks of sandstone and oxidized siltstone, up to 3 cm in diameter, make up 5 to 10 percent of this unit. A weak discontinuous stoneline occurs at the base of the unit, which rests unconformably on bedrock of the Monterey Group.

Age of Surficial Deposits

The modern surficial soil has developed in the youngest unit exposed in the Big Burn Road trench, colluvium C1 (Table 3). Two bulk samples of this organic soil were collected and submitted for radiocarbon dating of soil humates. Humates from the lower approximately 40 cm of the soil profile near station 15S gave a mean residence time (MRT) of 984 ±47 calibrated years B.P. Humates extracted from the second sample, which was collected from approximately 3 m south of the east end of the trench, yielded a MRT of 780 ±83 calibrated years B.P. (Table 2). Because these dates are MRT, we interpret that the soil has been accumulating carbon for roughly twice that long and, therefore, we judge unit C1 to be about 2,000 years old. Colluvium C2, the next youngest colluvial unit is constrained to be older than about 2000 years because it underlies C1. Based on the soil development of this unit, C2 is probably Holocene, although it may be as old as latest Pleistocene.

The antiquity of the oldest unit in the trench, colluvium C6, is suggested by clast lithology and stratigraphic and fault relationships. Laminated chert fragments are 5 to 10 times more abundant than other Monterey clast lithologies within this unit. This is peculiar because the hillslope directly west of (and above) the trench is underlain by sandstone and siltstone (Fig. 5), the predominant lithologies of the overlying colluvial sequence. The closest significant (very small amounts of laminated chert are present in the units exposed by the trench) outcrops of laminated chert (the Claremont Chert of the Monterey Group) and of chert-dominated float are about 100 m west of the trench where the hillslope gradually levels. This suggest that the landscape at the time colluvium C6 was deposited differed significantly from the present landscape. In addition, a relatively old age is indicated by a marked angular unconformity that separates this colluvium form the overlying colluvium (C5).

Exposed Faults

Five faults and numerous shears and fractures in a fault zone more than 30 m wide were exposed within the Big Burn Road trench (Plate 1). Four faults displace surficial deposits and strike subparallel to the northwest strike of the Miller Creek fault. The fifth fault, F5, is confined to rocks of the Contra Costa Group and strikes north. Three of the faults are steeply dipping and two faults have moderate dips. One low-angle shear, oriented subparallel to the ground surface and extending obliquely more than 9 m through colluvium C5, is interpreted to be a slide plane associated with a shallow landslide. We interpret faults F2 and F3 to be the main traces of the Miller Creek fault in the trench, based on stratigraphic relationships. Monterey Group bedrock occurs to the southwest of these faults and Contra Costa Group rocks occur to the northeast. The faults bound a 7-m-wide fissure or graben, suggesting that these faults may merge at depth.

The westernmost fault, F1, is exposed from the west end of the trench to the bottom of the exposure at station 7S (Plate 1). This planar fault is marked by a manganese(?)-oxide-stained gouge zone that is up to 20 cm wide and locally has a well-developed shear fabric. The fault and associated upward splaying shears form a fault zone 75 cm, or more, wide. The fault strikes N25°W to N36°W and dips 40° to 50° to the northeast. Slickensides plunge 37° to the northeast, indicating predominantly dip-slip movement on the fault. Colluvial units C2 and C4 in the hanging wall and unit CX in the footwall have been displaced along the fault. Unit C4 is arched in an anticline in the hanging wall of the fault indicating drag folding and contacts between subunits of C2 show lesser amounts of folding, suggesting progressive movement on the structure as these colluvial units were deposited (Fig. 6). Reverse displacement of unit C2, based on drag folding of the unit is approximately 0.2 to 0.5 m across F1.

A landslide origin is considered unlikely for this structure because of the failure mode, shear sense indicators, and the style of deformation along the fault. The best evidence for a tectonic, rather than landslide origin for this fault is structural and stratigraphic evidence. Shear sense indicators within the shear zone include well developed c and s surfaces (shears parallel to fault zone boundaries and internal foliation that asymptotically curves into these shears) and asymmetric tails on porphryoclasts (e.g., Simpson and Schmid, 1983, Passchier and Simpson, 1986). These structures are common within the fault zone (Plate 1) and strongly indicate reverse slip. The apparent anticlinal folding of colluvium C4, and to a lesser extent, C2, in the hanging wall of the fault (Fig. 6) is consistent with drag folding along a reverse fault rather than a roll over feature associated with landslide (normal fault sense of movement) movement. If the folding of C4 was associated with normal (landslide) slip, the unit would be folded in response to a shallowing of the slip plane with depth. According to structural models and analogs at a variety of scales, such a change in orientation of the fault plane should be significant and should occur updip on the fault from where the axial surface of the fold intersects the fault (e.g., Wernicke and Burchfiel, 1982). No such bend of the fault is observed.

In addition to the structural and stratigraphic arguments against a landslide origin for this fault, basic field relations are grossly inconsistent with the fault being a landslide slip plane. A landslide origin would indicate that an intact block of Monterey Group, at least 15 m long and 5 m (or more) thick, slid on a slide plane that "daylighted" on the hillslope and that the massive slide block continued to slide over the ground surface coming to rest on a layer of colluvium. Based on our detailed analysis of aerial photographs and field reconnaissance, numerous landslides have been identified along and near the trace of the Miller Creek fault. However, slump and lobate earthflows involving unconsolidated surficial materials are predominant, and no evidence for bedrock block slides was found.

Between faults F1 and F2, is a distributed zone of subparallel to anastomosing shears that tend to separate or juxtapose slivers of siltstone, sandstone, and mudstone of the Monterey Group. A few of these shears extend into overlying colluvium C4 between stations 4.5S and 7.5S (Plate 1). No offset of this unit was discernible along the shears.

The western edge of the graben is bounded by fault F2, which intersects the floor of the trench at station 8S (Plate 1). This downward-steepening fault is associated with a black (manganese-oxide-stained?), 5-cm-wide gouge zone. Planes within the fault zone curve asymptotically into the boundaries of the zone (similar to widely-spaced 's' surfaces) and indicate a reverse component of movement. The lower exposed section of the fault strikes N50°W across the trench and dips 79° to the northeast. The fault is associated with moderately dipping to subhorizontal shears within siltstone of the Monterey Group. Two of the associated shears or fractures could be traced a short distance into colluvium C6. The fault places colluvium C6 against Monterey Group bedrock.

We interpret the main fault in the Big Burn Road trench to be fault F3, which bounds the eastern edge of the graben between about stations 24S and 26S (Plate 1). In general this fault separates rocks of the Contra Costa Group to the northeast from the graben-fill deposit (C6) to the southwest. This high-angle anastomosing zone of subparallel faults is at least 1.5 m wide and may be as much as 3.5 m wide. The fault is associated with shear fabric, clay gouge zones, and vertically aligned clasts and elongate blocks of sandstone. In addition, a melange-like texture of sandstone fragments in a pervasively sheared fine-grained matrix within the westernmost Contra Costa Group also appears to be associated with the fault. Across the trench the fault zone strikes N33°-39°W and locally on the south wall individual fault traces have a more northerly strike (N20°-26°W), possibly suggesting a left-stepping pattern. The fault dips 74°W and, within 75 cm of the original ground surface, shallows to a dip of 43°W and forms a half-flower structure. The 74°W dip is similar to the 82°W dip estimated from the trace of the Miller Creek fault over the Big

Burn Rd. ridge. Slickenside stria on fault planes have trends ranging from N20°W to N59°W and have a range of plunges from 33°NW to 30°S, suggesting rotation of blocks within the fault zone.

Adjacent to and within the fault zone, sedimentary structures within the graben-fill deposit (C6) are oriented subparallel to this high-angle fault (Plate 1), indicating that the colluvium has been drag folded into parallelism as a result of shear on the fault. Internally, this clastic unit generally does not form or preserve shear fabric.

Two faults within fault zone F3 juxtapose colluvium C5 against colluvium C3, and several shears associated with the half-flower structure cut colluvium C3. The western of these two faults places unit C5 over unit C3 in an apparent reverse sense of movement, and the opposite stratigraphic relationship is exhibited across the eastern fault. The net vertical separation of the base of colluvium C3 projected across the fault zone in either trench wall is difficult to constrain because it is missing between faults F3 and F4 (Plate 1). Colluvium C5 and C1 in the south wall and colluvium C1 in the north wall directly overlie the fault trace. In both trench walls these units appear to be slightly arched over the fault. The arching of colluvium C1 is most apparent on the south wall where a weakly developed stoneline has a convex form (Fig. 7).

Intersecting the floor of the trench between stations 28S and 29S is a planar, moderately east-dipping fault zone, F4, consisting of several imbricate fault traces (Plate 1). The fault is associated with red and black gouge zones, shear fabric, and isoclinal folds. Bedding within the Contra Costa Group is oriented parallel to subparallel to the fault. A disrupted carbonate(?)-cemented sandstone bed in the hanging wall is boudinaged. The largest boudin is bounded by shear surfaces that sigmoidally curve into the boundaries of the shear zone also indicating a reverse sense of displacement. A similarly disrupted pebble conglomerate bed in the footwall has been drag folded into an isoclinal anticline-syncline fold pair. A distinct mullion could be traced up-dip to a small rock fragment embedded in the fault plane of the footwall, clearly showing reverse slip on fault.

In the north trench wall and particularly in the south wall imbricate shears cut colluvium C3. These shears extend to within 40 cm of the original ground surface in the south wall.

The easternmost fault, F5, in the Big Burn Road trench is a single undulatory shear plane juxtaposing sandstone on the northeast against siltstone to the southwest (Plate 1). The fault strikes N4°W across the trench and dips 62°W in the south wall but dips steeply to the east in the north wall. Slickensides trend N87°E and plunge 39°N. This fault appears to be confined to the bedrock of the Contra Costa Group and is overlain by unbroken colluvium.

Evaluation of the Big Burn Road Site

The predominance of high-angle structures, a large-scale apparently extensional graben filled with colluvium, and tectonic inversion of this graben, and a half-flower structure along the main fault (i.e., F3), and the overall steep (60 to 82°; 82° in vicinity of Big Burn site) dip of the fault indicated by the fault trace over topography, show that deformation on the Miller Creek fault is dominantly strike-slip. The dip slip component of movement associated with many of the faults and shears is reverse, indicating a probable reverse component of movement on the fault. Slickenside plunges and shear sense criteria do not distinguish between right or left lateral sense of displacement. The approximate parallelism of the strike of the Miller Creek fault and the dextral Hayward fault, and other major strike-slip faults of the San Andreas fault system indicates that the expected sense of lateral slip on the fault is dextral. The indicated strike slip movement on the Miller Creek fault differs markedly from the purely contractional deformation suggested in previous studies of the fault (Wakabayashi et al., 1992). A lateral component seems to best explain the preponderance of Claremont chert fragments within the graben-fill deposit (i.e., unit C6). The interpreted dextral sense of movement on the fault is also consistent with the long term (past 10 million years) evolution of this fault zone as part of a zone of major dextral slip (Wakabayashi, in review).

Deposition of colluvium C6 appears to have been synchronous with formation of the graben, which occurred by movement on the bounding faults (i.e., F2 and F3). The angular discordance between this graben-fill unit with the overlying colluvium, suggests that most of the deformation associated with this main fault zone predates unit C5.

However, as discussed above, faults within the Big Burn Road trench clearly cut colluvial units C3 and C4 and one fault displaces the lower subunits of colluvium C2. In addition, the base of colluvium C1 is arched over the main fault in both walls of the trench.

Although this minor deformation is spatially associated with the underlying main fault, we cannot rule out the possibility that arching of unit C1 was produced by non-tectonic processes. No shears or fractures within this unit were noted in association with the gentle apparent fold. The amplitude of folding at the base of colluvium C1 appears to be greater than the amplitude of folding of the base of underlying colluvium (i.e., unit C5) on the south wall. There is no net vertical offset of the base of the unit in the vicinity of the fault, although this variation in apparent separation is consistent with the dominantly strike-slip movement interpreted for the fault. The vertisolic structure of the modern soil developed within this unit and of the subjacent buried soil signifies the presence of highly expansive clay minerals. Thus, folding of unit C1 results from either expansion of near surface clays or from movement on the underlying fault.

DISCUSSION

Although previous studies have suggested a dominant or significant reverse sense of movement on the Miller Creek fault (Wakabayashi et al., 1992), our study indicates that the late Quaternary movement along this fault is predominantly strike slip.

The timing of the most recent paleoearthquake on the Miller Creek fault is not well constrained, primarily because folding of colluvium C1 in the Big Burn Road trench over the main fault may be related to either heave associated with swelling of expansive clay minerals or to recent faulting. However, if folding of colluvium C1 is related to the most recent paleoearthquake, the event occurred after deposition of deposit C1, which yielded MRT of 700 to 1,000 years. This implies that the event occurred in the past 2,000 years. The youngest unequivocally faulted unit at the Big Burn site is colluvium C2 that is probable Holocene (and pre-2000 years), but can permissibly range in age from latest Pleistocene to mid Holocene.

The minor folding of unit C1 in the Big Burn Road trench and the absence of Holocene faulting at the King Canyon site, suggest that if this deformation resulted from the most recent event, it may have been a relatively small earthquake, near the lower limit of surface rupturing events (~M6; Wells and Coppersmith, 1994). However, the lateral component of movement on the hypothetical event is unconstrained, so the amount of slip during the event may be somewhat larger than the impression given by the vertical deformation. The extent of hypothetical surface rupture to the southeast is unknown. The total length of the Miller Creek and Palomares faults to the south is approximately 35 km, but there is insufficient field data from the southern part of the fault to evaluate the continuity of the fault, let alone similarity in recency of movement along it.

Trench exposures at the King Canyon site provide positive evidence for an absence of movement at that location on the northern Miller Creek fault during the past 16,000 years (or more). Faulted unit C2 at the Big Burn Road is almost certainly younger than the unfaulted deposits at the King Canyon site, so the recency of movement at the two sites is different. The fault also has a shallower dip and more westerly strike at the King Canyon fault, so there may be a geometric basis for segmentation of the fault, or different fault behavior at the two sites. The difference in dip is consistent with a higher dip slip component for the more northwesterly striking part of the fault, contrasted with the steep fault dip and evidence for strike-slip faulting at the Big Burn Road site.

It is difficult to put precise constraints on the slip rate of the Miller Creek fault because of the lack of piercing point data to constrain lateral slip that is probably the dominant component of movement. The stratigraphic relationships in the Big Burn Road trench suggest probable long recurrence interval for such events (thousands of years). The indicated long recurrence intervals, and the comparative proximity of the much more active Calaveras and Hayward faults indicates that the Miller Creek does not pose a significant earthquake hazard. For deterministic seismic hazard, the proximity of the Hayward and Calaveras faults to any region along the Miller Creek fault, coupled with estimated larger maximum earthquakes on these two faults, indicates that these two major strike-slip faults should be the controlling seismic sources for most (but not necessarily all) of the area near to the Miller Creek fault. For probabilistic hazard the Miller Creek fault will have negligible impact on the total seismic hazard of adjacent regions because the recurrence intervals associated with the fault are probably at least an order of magnitude longer (and the maximum earthquake smaller) than the nearby Calaveras and Hayward faults.

The evidence for a dominantly strike-slip mode of late Quaternary movement for the Miller Creek fault indicates that East Bay Hills should not be viewed as a purely contractional domain. In fact, contractional deformation in this domain may be subordinate to strike-slip deformation. Future paleoseismic investigations of faults in the East Bay Hills, need to consider the possibility of dominantly lateral slip if slip rate estimates are to be constrained.

The late Quaternary slip rate on the Miller Creek fault, although poorly constrained, certainly must be considerably lower than the long-term late Cenozoic average, that may be as high as 3+ mm/yr, based on 35 km of estimated displacement in this domain in the last 10 million years (Wakabayashi 1997; Wakabayashi, in review). Although there are certainly well-documented folds and low-angle faults in this region, significant late Quaternary shortening rates in this region have yet to be demonstrated. It is possible that the observed shortening of late Cenozoic rocks, took place prior at higher rates than the late Quaternary rates during earlier periods, analogous to the slow down in dextral slip rates through this region.

If significant amount (1 to 2 mm/yr or more--from the uncertainties of the Hayward and Calaveras fault slip rates) of dextral slip rate passes through the East Bay Hills, it apparently is *not* accommodated on the Miller Creek fault. If such deformation indeed passes through this region, it must be accommodated on other faults, such as the Cull Canyon-Moraga fault, or faults splaying westward from the northern Calaveras fault, such as the Bolinger and Las Trampas faults.

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REFERENCES

Argus, D.F., and Gordon, R.G., 1991, Current Sierra Nevada-North America motion from very long baseline interferometry: Implications for the kinematics of the western United States: Geology, v.19, p. 1085-1088.

Aydin, A., and Page, B.M., 1984, Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay region, California: Geological Society of America Bulletin, v. 95, p. 1303-1317.

Bochardt, G., Lienkaemper, J.J., and Schwartz, D.P., 1990, Soil development and tectoturbation in a toposequence produced by Holocene downwarping along the Hayward fault, Fremont California: *in* Soil Development and Displacement along the Hayward Fault, Volume I, Fremont, California, California Division of Mines and Geology Open-File Report 88-12, Chapter B, p.55-124.

Buising, A.V., and Wakabayashi, J., 1996, Active folds and thrusts in the Upper San Leandro Reservoir area, eastern San Francisco Bay area, California: in Jayko, A.S., and Lewis, S.D., compilers, Toward Assessing the Seismic Risk Associated with Blind Thrust Faults: U.S. Geological Survey Open File Report 96-267, p. 119-126.

Crane, R.C., editor, 1988, Field trip guide to the geology of the San Ramon Valley and environs: Northern California Geological Society Field Trip Guidebook.

ESA (Earth Sciences Associates), 1991, consultant report to the East Bay Municipal Utility District

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1994, Preliminary geologic map emphasizing bedrock formations in Contra Costa County, California: United States Geological Survey Open File Report 94-622.

Ham, C.K., 1952, Geology of Las Trampas Ridge, Berkeley Hills, California: California Division of Mines and Geology Special Report 22, 26pp.

Helley, E.J., Lajoie, K.R., Spangle, W.E., and Blair, M.L., 1979, Flatland deposits of the San Francisco Bay region California—Their geology and engineering properties, and their importance to comprehensive planning: U.S. Geological Survey Professional Paper 943, 88p.

Jones, D.L., Graymer, R., Wang, C., McEvilly, T.V., and Lomax, A., 1994, Neogene transpressive evolution of the California Coast Ranges: Tectonics, v. 13, p. 561-574.

Kelson, K.I., and Simpson, G.D., 1994, Late Pleistocene deformation of the southern East Bay Hills based on fluvial terraces along Alameda Creek, Sunol Valley to Fremont, California: EOS, v. 75, no. 44, p. 682.

Kelson, K.I., Lettis, W.R., Lisowski, M., 1992, Distribution of geologic slip and creep along faults in the San Francisco Bay region: in Borchardt, G., and others, eds. Proceedings of the Second Conference on Earthquake Hazards in the eastern San Francisco Bay area: California Division of Mines and Geology Special Publication 113, p.31-38.

Kelson, K.I., Simpson, G.D., Lettis, W.R., Haradan, C.C., Williams, C.R., and Thompson, S.C., 1994, Holocene slip rate and recurrence of the northern Calaveras fault at Leyden Creek, Alameda County, California: in Proceedings of the Workshop on Paleoseismology, U.S. Geological Survey Open File Report 94-568, p. 94-95

Lienkaemper, J.J., Borchardt, G., and Lisowski, M.,1991, Historic creep rate and potential for seismic slip along the Hayward fault, California, Journal of Geophysical Research, 96, 18261-18283.

Oppenheimer, D.H., and Lindh, A.G., 1992, The potential for earthquake rupture of the northern Calaveras fault: in Borchardt, G., ed., Proceedings of the 2nd Conference on Earthquake Hazards in the eastern San Francisco Bay Area, Calif. Div. Mines and Geology Special Publication 113, p.233-240.

Oppenheimer, D.H., Wong, I.G., and Klein, F.W., 1992, The seismicity of the Hayward fault, California: in Borchardt, G., ed., Proceedings of the 2nd Conference on Earthquake Hazards in the eastern San Francisco Bay Area, Calif. Div. Mines and Geology Special Publication 113, p.91-100

Passchier, C. W., and Simpson, C., 1986, Porphryoclast systems as kinematic indicators: Journal of Structural Geology, v.8, p. 831-843.
Schwartz, D.P., Pantosti, D., Hecker, S., Okumura, K., Budding, K., and Powers, T., 1992, Late Holocene behavior and seismogenic potential of the Rodgers Creek fault zone, Sonoma County, California: in Borchardt, G., ed., Proceedings of the 2nd Conference on Earthquake Hazards in the eastern San Francisco Bay Area, Calif. Div. Mines and Geology Special Publication 113, p. 393-398.
Shlemon, R.J., 1981, Soil-geomorphic analyses, Contra Loma Dam Geotechnical Investigations, Contra Costa and Alameda Counties, California: *in* Seismotectonic Study of Contra Loma Dam and Vicinity, unpublished report by Earth Sciences Associates submitted to the U.S. Bureau of Reclamation, Denver, Colorado, Appendix B, 13 p.
Simpson, C. and Schmid, S., 1983, An evaluation of criteria to deduce the sense of movement in sheared rocks: Geological Society of America Bulletin, v. 94, p. 1281-1288
Unruh, J.R., and Lettis, W.R., 1998, Kinematics of transpressional deformation in the eastern San Francisco Bay region, California: Geology, v. 26, p. 19-22.
Unruh, J.R., and Sawyer, T.L., 1995, Late Cenozoic growth of the Mt. Diablo fold and thrust belt, central Contra Costa County, California and implications for transpressional deformation of the northern Diablo Range: American Association of Petroleum Geologists Bulletin, v. 79, p. 600.
Unruh, J.R., and Sawyer, T.L., 1997, Assessment of blind seismogenic sources, Livermore Valley, eastern San Francisco Bay region: Final Technical Report, U.S. Geological Survey, National Earthquake Hazards Reduction Program, 88 pp.
Wagner, J.R., 1978, Late Cenozoic history of the Coast Ranges east of the San Francisco Bay: Ph.D. Thesis, University of California, Berkeley, 161 pp.
Wagner, D.L., Bortugno, E.J., and McJunkin, R.D., 1991, Geologic map of the San Francisco-San Jose quadrangle: California Division of Mines and Geology, Regional Geologic Map Series, Map No. 5A
Wakabayashi, J., 1997, Rationale for limited post-Eocene slip on the Pilarcitos fault and a working model for slip distribution and evolution of the northern San Andreas fault system: EOS, v. 78, no. 46, p. F703
Wakabayashi, J., and Hengesh, J.V., 1995, Distribution of late Cenozoic displacement on the San Andreas fault system, northern California: in Sangines, E.M., Andersen, D.W., and Buising, A.W., eds., Recent geologic studies in the San Francisco Bay Area, Pacific Section, SEPM (Society for Sedimentary Geology), Book. 76, p.19-30
Wakabayashi, J., and Hengesh, J.V., 1998, 4-D processes in transform fault systems: progressive development of step-overs and bends: Geological Society of America, Abstracts with Programs, v. 30, no.7, p.A74-A75
Wakabayashi, J., Smith, D. L., and Hamilton, D. H., 1992, The Miller Creek Fault and related structures: Neogene kinematics of a potentially active thrust system in the East Bay Hills, California: in Borchardt, G., ed., Proceedings of the 2nd Conference on Earthquake Hazards in the eastern San Francisco Bay Area, Calif. Div. Mines and Geology Special Publication 113, p. 345-354.
Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Seismological Society of America Bulletin, v. 84, p. p. 974-1002
Wernicke, B., and Burchfiel, B.C., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, p. 104-115

TABLE 1
Soil Profile[1] Description No. 1

Location: King Canyon trench, station 11S; Date: Sept. 30, 1997; Describer: T.L. Sawyer; Physiographic Position: Mid-alluvial-fan summit; Slope & Aspect: =2%NW; Elevation: ~420 ft; Parent Material: Silty clay loam over clay loam (alluvium) with sandstone, siltstone, and chert clasts; Climate: Mediterranean with mean annual temperature of 13.6°C (Oakland Airport); Vegetation: Modern vegetation is artificially maintained pine and fir trees; native vegetation probably chapparal and annual grasses.

Horizon	Depth (cm)	Color[2] Dry	Moist	Texture	Structure	Consistence Dry	Wet	Boundary	Pores	Roots	2ndry $CaCO_3$	Clay Films
A	0-8	10YR3/2	10YR2/1	sicl	2-3fg	h	s/p	cw	--	3m-f	none	none
AB	8-20	10YR2/1	10YR2/1	sicl	3m-csbk	vh-h	s/p	as	--	2m-f	none	none
Bt	20-110	10YR2/1	10YR2/1	sic	3c-vcab	vh-h	s/vp	as	--	2m-f	none	2npf
2Btb[1]	110-195	10YR2/1	2.5Y2/0	sic	3m-cpr	vh	s/vp	as	--	1m-f	none	3mkpf
3Bt1b2 2	195-236	10YR2/2	10YR3/3	c	2-3c-msbk	sh	s-vs/vp	as	det	none	none	3npf 3kpo
3Bt2b[2]	236-280	10YR4/4	10YR2/2	gcl	1-2msbk	sh	s/p	as	det	none	none	1npf 2-3mkpo
3CBb[2]	280-300	--	2.5Y4/2	scl	1sbk	sh	s/p	as	det	none	none	1npf 2-3mkpo
4Cb[2]	300-370+	--	5B4/1	cl	m	sh	ss/p	n/a	--	none	none	none

[1] Soil profile descriptions follow procedures and use abbreviations in the New Soil Survey Manual (USDA, 1981).
[2] Soil color and notation based on Munsell Soil Color Chart (Munsell Color Company, Inc.).

Comments: Three samples of charcoal fragments (RC1, RC2, RC3) were collected from a depth of 300-320 cm within horizon 4Cb2. These samples yielded dates of 6190 ±50, 16,330 ±60, and 6,320 ±50 ^{14}C yr, respectively. [1]Stratigraphic and pedogenic relations indicate horizon is an erosionally truncated buried soil. [2]Stratigraphic and pedogenic relations indicate horizon is top of an erosionally truncated lower buried soil.

TABLE 2
Radiocarbon Dates from the Miller Creek Fault Trenches

Sample Field ID Sample Location[1]	**Lab #**	**^{14}C Date** (yrB.P.)	Corrected **^{14}C Date** (yrB.P.)	**Comments**
RC1—King Canyon trench, station 11.2S-3.45	GX-23778-AMS[2]	6,190± 50		Small charcoal fragment (1.5cm x 1cm x 1cm)
RC2—King Canyon trench, station 10.6S-3.45	GX-23779-AMS2	16,330± 60		Several small charcoal fragments in close proximicity
RC3—King Canyon trench, station 11S-3.4	GX-23780-AMS[2]	6,320± 50		Two small fragments (2 cm x 1.5 cm x 0.5 cm & 1 cm x 1 cm x ?0.5 cm) of carbonized wood in close proximicity
RC4—Big Burn Road trench, station 15S-1.5	3464[3]	1,016± 45	984±47	Mean residence date on soil humates extracted from bulk organic soil sample
RC5—Big Burn Road trench, station 31S-0.8	3465[3]	816±81	780±83	Mean residence date on soil humates extracted from bulk organic soil sample

[1]Sample location given in trench coordinates, for example, station 11.2S-3.45 is 11.2 m from east end of trench in the south wall and is 3.45 m below the 0 m datum.

[2]Geochron Laboratories, Krueger Enterprises, Inc., Cambridge, Massachusetts

[3]Desert Research Institute, University of Nevada, Las Vegas, Nevada

TABLE 3
Soil Profile Description No. 2

Location: Big Burn trench, station 20S; Date: Oct. 22, 1997; Describer: T.L. Sawyer; Physiographic Position: Rounded ridge-crest-saddle shoulder; Slope & Aspect: =30%NW; Elevation: ~740 ft; Parent Material: Silty clay loam over clay loam (colluvium) with sandstone, siltstone, and chert clasts; Climate: Mediterranean with mean annual temperature of 13.6°C (Oakland Airport); Vegetation: Probably chapparal and annual grasses.

Horizon	Depth (cm)	Colorë Dry	Colorë Moist	Tex-ture	Stru-cture	Consistence Dry	Consistence Wet	Boun-dary	Pores	Roots	2ndry $CaCO_3$	Clay Films
A	0-13	10YR5/3	10YR4/2	sil	2cg 1msbk	h	ss/sp-p	cw	1vf	3f	none	none
AB	13-43	10YR4/2	10YR2/1	sil	1m-csbk	h-sh	ss/p	as	3m-cv	1f	none	none
2Bt1b[1]	43-70	10YR6/3	10YR4/3	c	3cpr 2fabk	eh	vs/vp	gw-gb	--	--	none	1npf[3]
2Bt2b	70-90	10YR7/4	2.5Y5/4	c	3c-vcabk	eh	s/vp	as	--	--	none	1mkpf
3Bt3b	90-118	10YR6/2	10YR4/3	c	2mabk	h	s/vp	vas	1vfv	none	none	3npf
4Bt4b	118-125	10YR6/4	10YR4/4	sic	2c-vcabk	h	s-ss/p	as	--	none	none	1npf
5Btb2[2]	125-178+	10YR7/3	10YR5/3	c	1msbk	h-sh	vs/p	n/a	--	none	none	3n-mkbr-pf

[1]Soil profile descriptions follow procedures and use abbreviations in the New Soil Survey Manual (USDA, 1981).

[2]Soil color and notation based on Munsell Soil Color Chart (Munsell Color Company, Inc.).

Comments: A bulk organic soil sample (RC4) was collected from a depth of 10-50 cm within the surficial soil at station 15S, which yielded a MRT of 984±47 cal B.P. A second bulk soil sample (RC5) was collected from a depth of 20-50 cm within the surficial soil at station near 31S, which yielded a MRT of 780±83 cal B.P. [1]Stratigraphic and pedogenic relations indicate horizon is top of an erosionally truncated buried soil. [2]Stratigraphic and pedogenic relations indicate horizon is top of an erosionally truncated lower buried soil. [3]Translocated silt forms common, thick coatings on some ped faces.

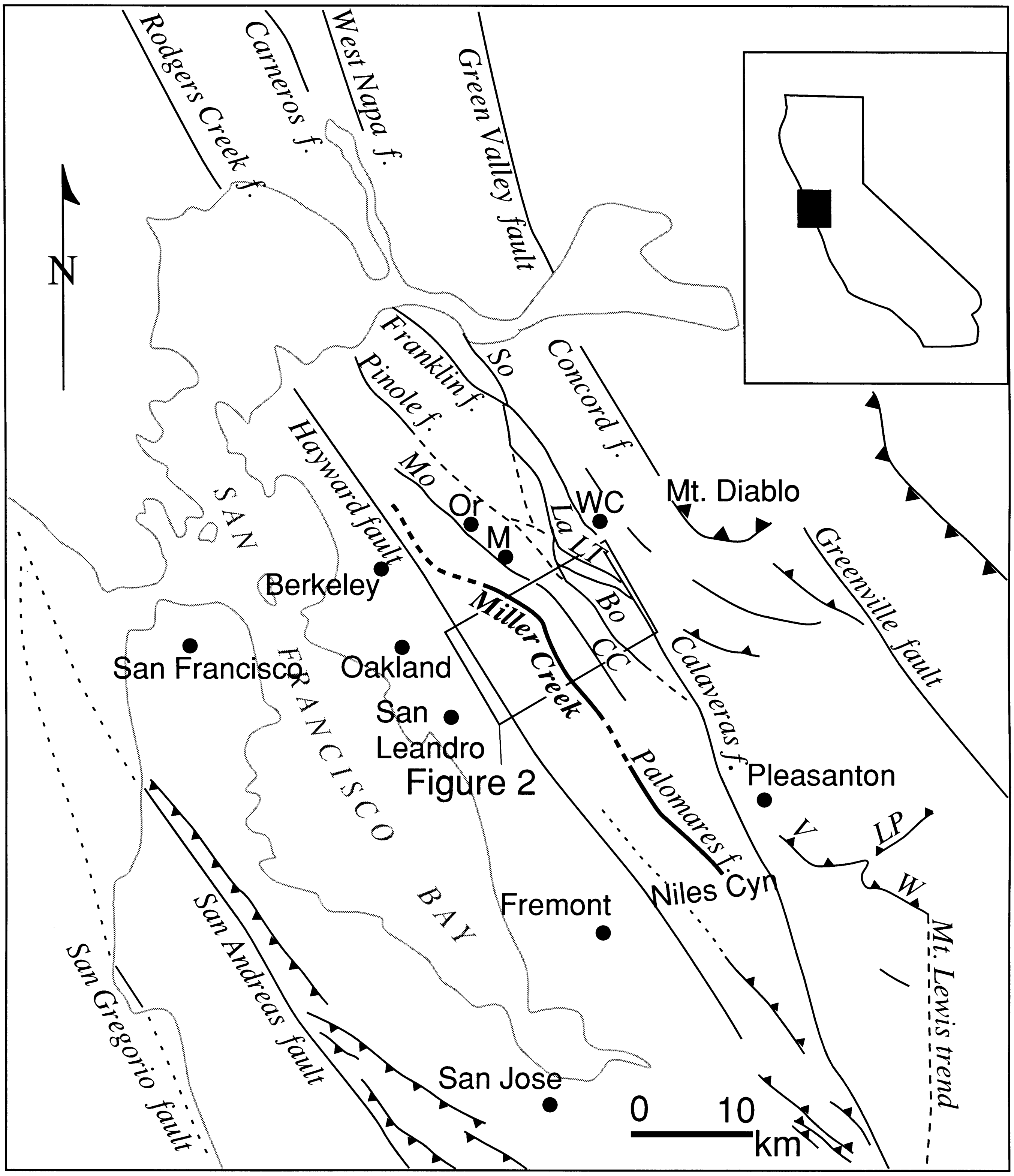


Figure 1: Map showing the Miller Creek fault, major strike slip faults of the San Andreas fault system and contractional faults of the San Francisco Bay area. Map adapted from Aydin and Page (1984), Wagner et al. (1991), Wakabayashi et al., (1992), Graymer et al. (1994), Buising and Wakabayashi (1996). Abbreviations: Towns (non-Italic): M=Moraga, O=Orinda; Faults (Italic): Bo=Bolinger, CC= Cull Canyon, La=Lafayette, LP= Las Positas, LT=Las Trampas, Mo=Moraga, So=Southampton, V=Verona, W=Williams

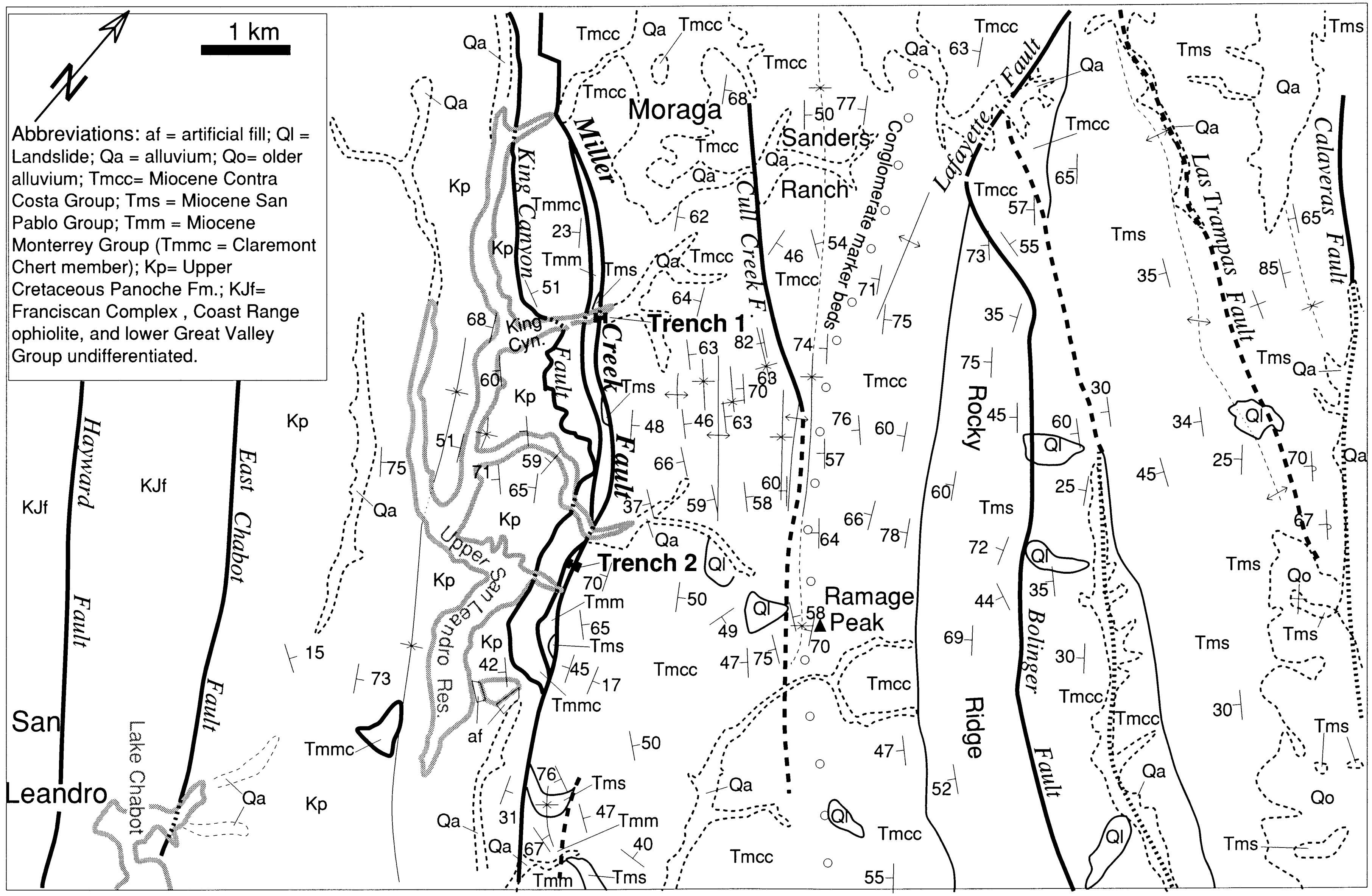


Figure 2: Geology of the Upper San Leandro Reservoir area. Adapted from Wakabayashi et al. (1992).

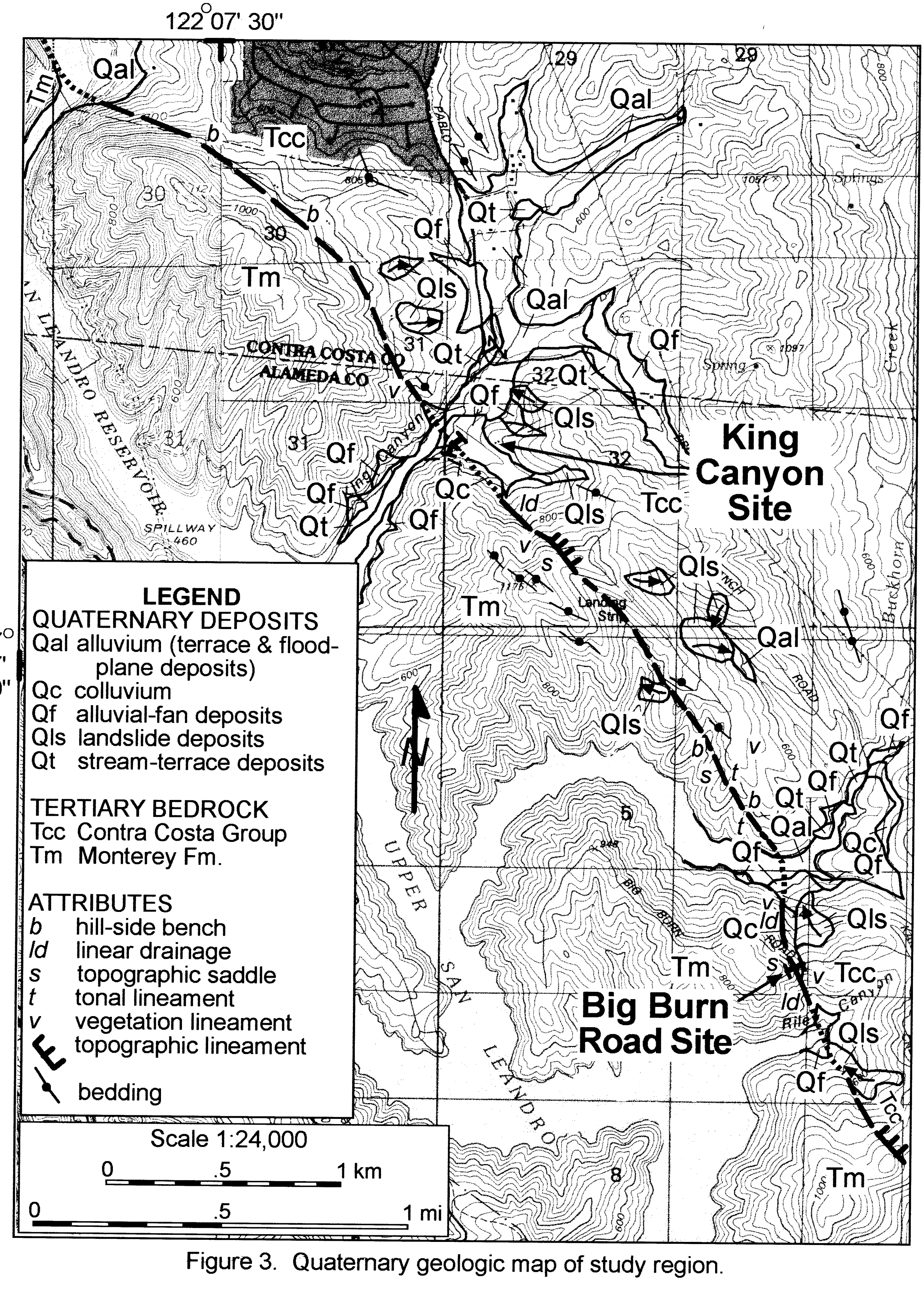
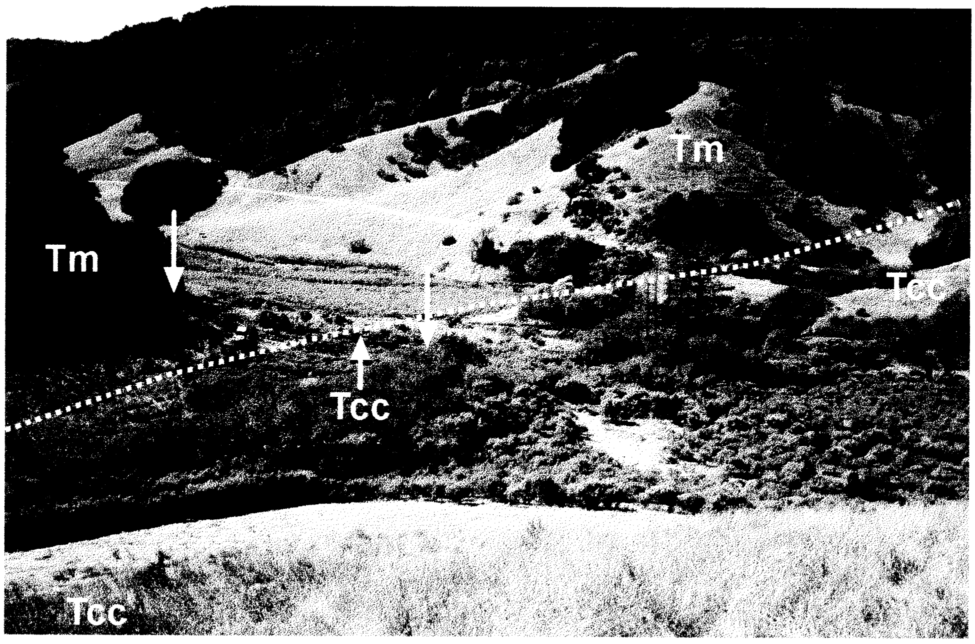


Figure 3. Quaternary geologic map of study region.

(a)



(b)

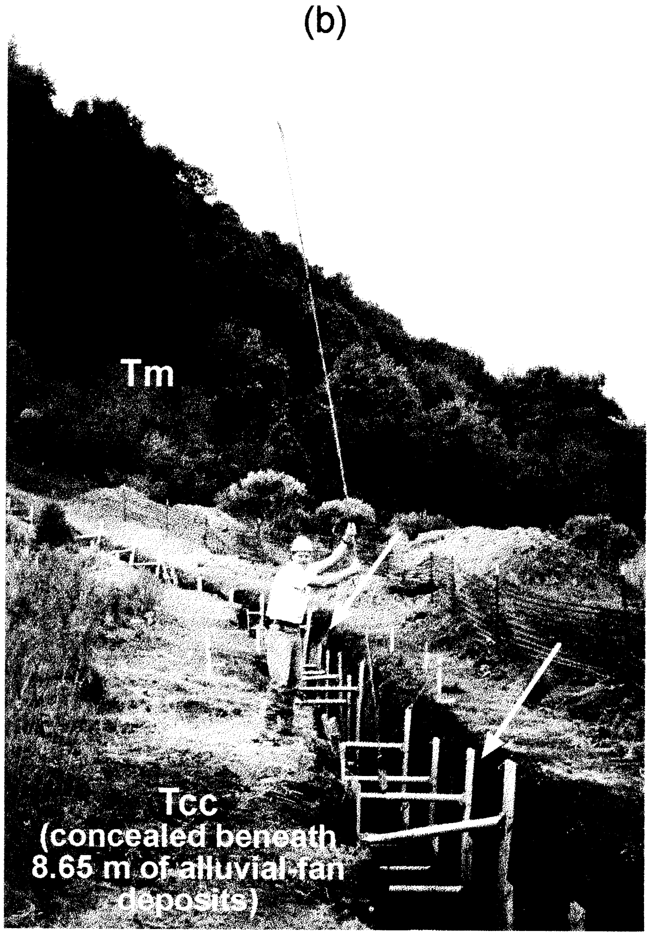
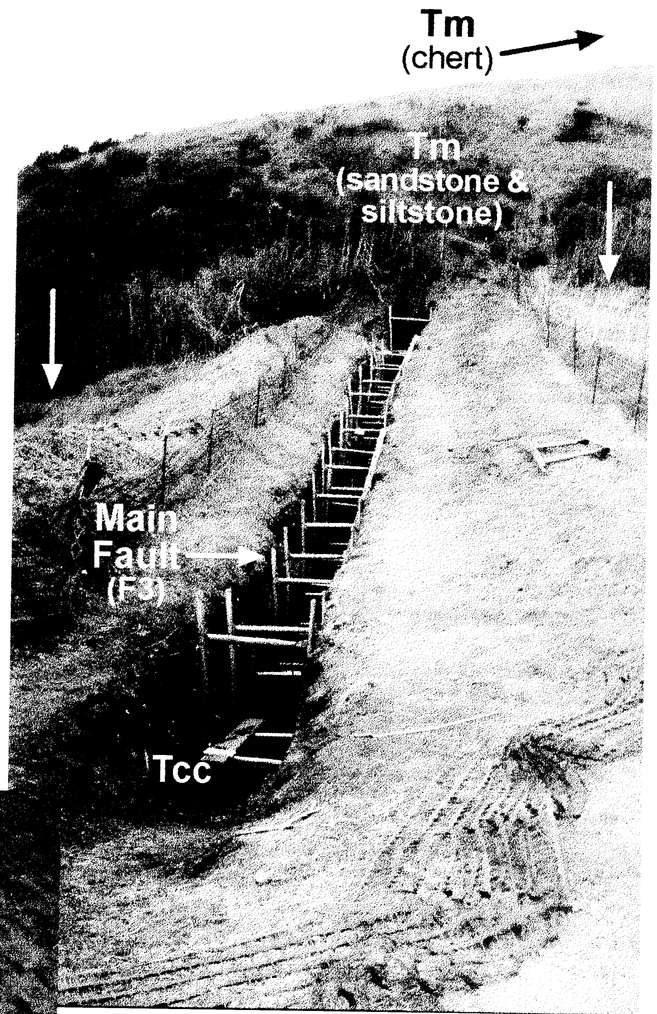


Figure 4. (a) Photograph looking northwest into King Canyon at the King Canyon trench (between downward-pointing arrows), showing location of hand-auger hole (upward-pointing arrow), inferred location of the concealed Miller Creek fault (dotted line), and general distribution of the Monterey Fm. (Tm) and Contra Costa Group (Tcc). (b) Photograph looking westward across surface of alluvial fan and colluvial slope at steep hillslope underlain by Monterey Fm. Geologist is holding hand auger directly above where a boring was augered into the floor of the King Canyon trench to a depth of 9.5 m below the ground surface. Weathered rock of the Contra Costa Group was encountered at a depth of 8.65 m, constraining the location of the Miller Creek fault between this boring and exposures of the Monterey Fm. in the trench (i.e., between arrows).

(a)



(b)

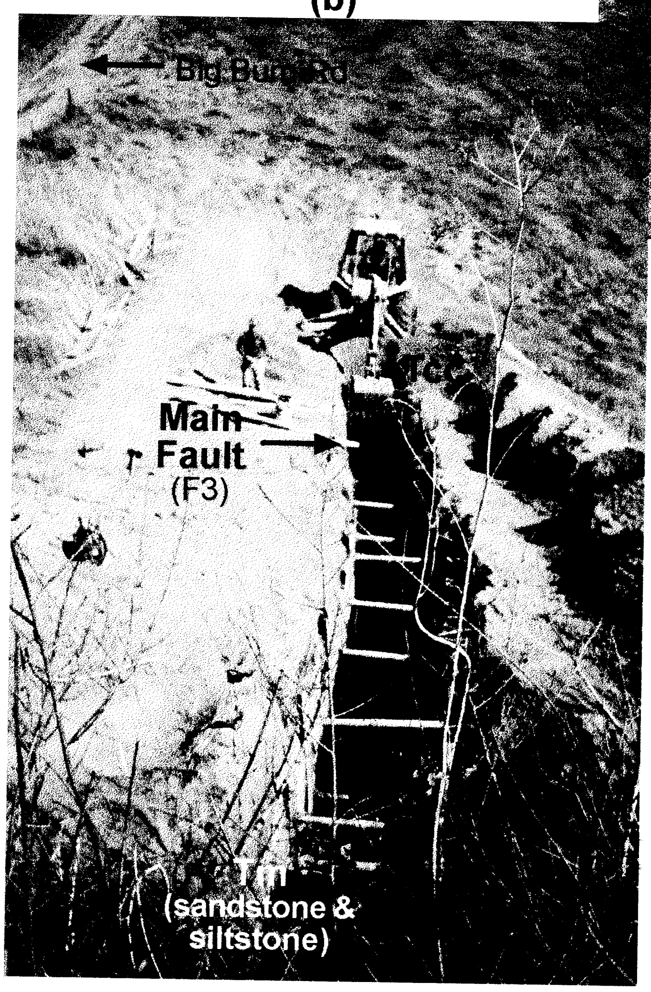


Figure 5. Photographs of the Big Burn Road site showing approximate location of the inferred main fault (F3) exposed in the Big Burn Road trench and the general distribution of the Monterey Fm. (Tm) and Contra Costa Group (Tcc) at the site. (a) Looking westward at vegetation lineament (vertical arrows) along base of steep escarpment underlain by sandstone and siltstone of the Monterey Fm. Black arrow points to nearest outcrops and float of predominantly chert composition.
(b) Looking eastward into topographic saddle atop Riley Ridge and south of Big Burn Road, as the trench was being excavated.

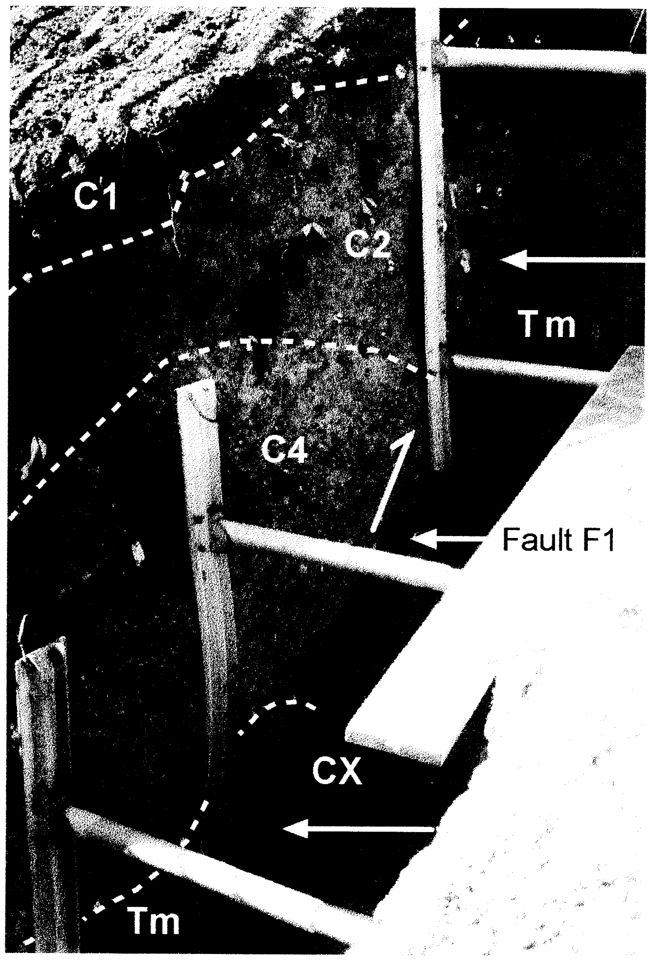


Figure 6. Photograph of west end of Big Burn Road trench showing relationships among colluvial deposits (units C1, C2, C4 and CX), fault F1 (horizontal arrows), and bedrock of the Monterey Fm. (Tm). Note apparent anticlinal geometry of colluvium C4.

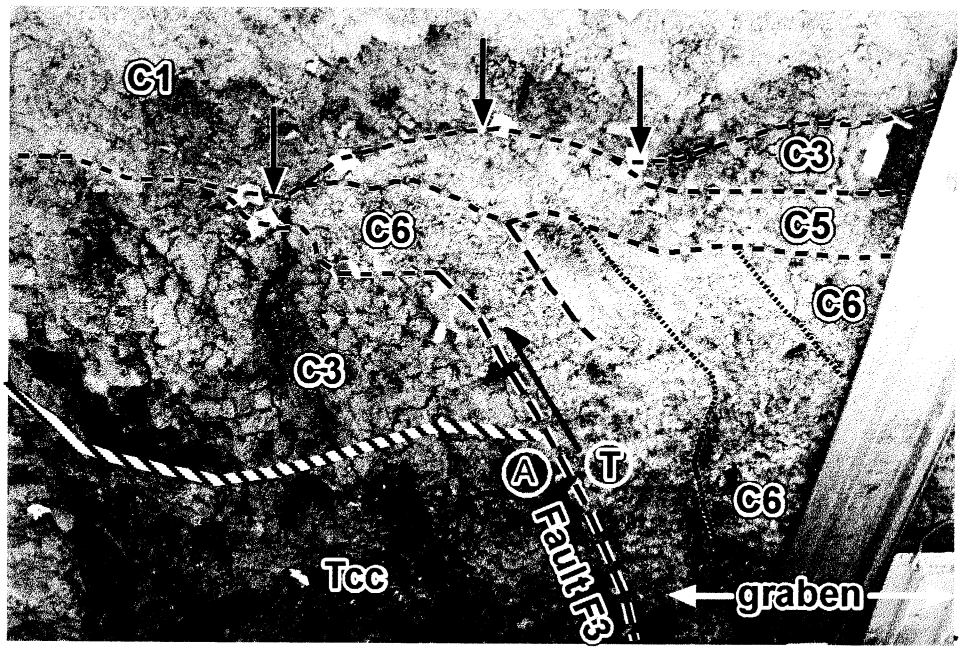


Figure 7. Close-up photograph of fault F3 on south wall of the Big Burn Road trench showing the apparent arching of the base of colluvium C1 (vertical arrows) and inferred lateral-slip component on this graben-bounding fault. The fault places graben-fill (C6) against Contra Costa Group (Tcc) and, in an apparent reverse sense, over colluvium C3. Note sedimentary structures within colluvium C6 (dotted lines) are subparallel to fault and are truncated by an angular unconformity at the base of colluvium C5.